The Neutron-neutron Scattering Length Using the Radiative π^- Capture Reaction in Deuterium

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Charge symmetry breaking (CSB) in the nuclear force results from the difference in masses of the d and u quarks, which is reflected in the different hadron (e.g., neutron and proton) masses and the mixing of mesons exchanged in the interaction of two nucleons (e.g., $\rho - \omega$ and $\pi - \eta$) [1]. The difference between the neutron-neutron (*nn*) and proton-proton (*pp*) scattering lengths ($a_{nn} - a_{pp}$) is one of the few experimental quantities that provides a measure of the magnitude of CSB. The value of a_{pp} is measured directly in proton-proton scattering—the primary error comes from the uncertainty in modeling electromagnetic effects due to the Coulomb scattering of the two charged protons. The resulting value for a_{pp} is -17.3 $\pm$ 0.005 (expt) $\pm$ 0.4 (thy) fm. Until direct measurement of a_{nn} is made, we must rely upon the analysis of three-body final states in few-nucleon reactions.

An impressive number of determinations of a_{nn} have been made using neutron-induced deuteron breakup. However, there are significant discrepancies among a_{nn} values obtained from different neutron-deuteron (nd) breakup experiments. Therefore we analyzed the theoretical uncertainty in radiative π^- capture by deuterium (see Fig. 1), because there are only two strongly interacting particles (two neutrons) in the final state, along with a photon that interacts with the two hadrons only electromagnetically [2,3]. This analysis was employed in two experiments at the Paul Scherrer Institut (PSI) in Switzerland by a Laussane-Zuerich-Muenchen collaboration. The first determination was a kinematically incomplete measurement in which only the γ-ray spectrum was obtained, resulting in a value for a_{nn} of -18.6 $\pm$ 0.5 fm that includes a theoretical uncertainty of $\pm$ 0.3 fm. [4-6]. The second determination was a kinematically complete measurement in which the neutron time-of-flight spectrum was measured along with the γ-ray spectrum. The value of a_{nn} was determined to be 18.7 $\pm$ 0.6 fm, which again includes a theoretical uncertainty of $\pm$ 0.3 fm [4-6].

Because of the large variance in values of a_{nn} obtained from kinematically complete and incomplete nd breakup experiments, the recommended value for a_{nn} was a combined value from the two radiative $\pi^- d$ capture experiments by the same experimental group. Therefore, a new measurement was proposed at Los Alamos Meson Physics Facility (LAMPF now known as LANSCE). Our theoretical analysis again explored the sensitivity of the extracted value of the scattering length to the numerous aspects of the model. The two largest uncertainties were confirmed to arise from the short-range characterization of the *nn* final-state wave function and from the treatment of the pion wave function in the initial state. We reconfirmed that the value of a_{nn} could indeed be extracted from a kinematically complete experiment with a theoretical uncertainty of less than 0.3 fm.

A conclusive analysis of the LAMPF kinematically complete capture-at-rest $^2H(\pi^-,n\gamma)$n reaction measurement has now been completed and was recently published [7]. High precision neutron time-of-flight measurements and high spatial resolution γ-ray detection enabled the experimentalists to make a detailed assessment of the systematic uncertainties in the experiment. The resulting value of a_{nn} was determined to be -18.63 $\pm$ 0.10 (stat) $\pm$ 0.44 (sys) $\pm$ 0.30 (thy) fm. Combining this LAMPF result with the previous PSI measurements gives a world average value of a_{nn} = -18.63 $\pm$ 0.27(expt) $\pm$ 0.30(thy) fm. The value of a_{nn} when corrected for the magnetic moment interaction of the two neutrons [1] is then -18.9 $\pm$ 0.4 fm. This differs from the recommended value for app by 1.6 $\pm$ 0.5 fm, thereby confirming charge symmetry breaking at the 1% confidence level.

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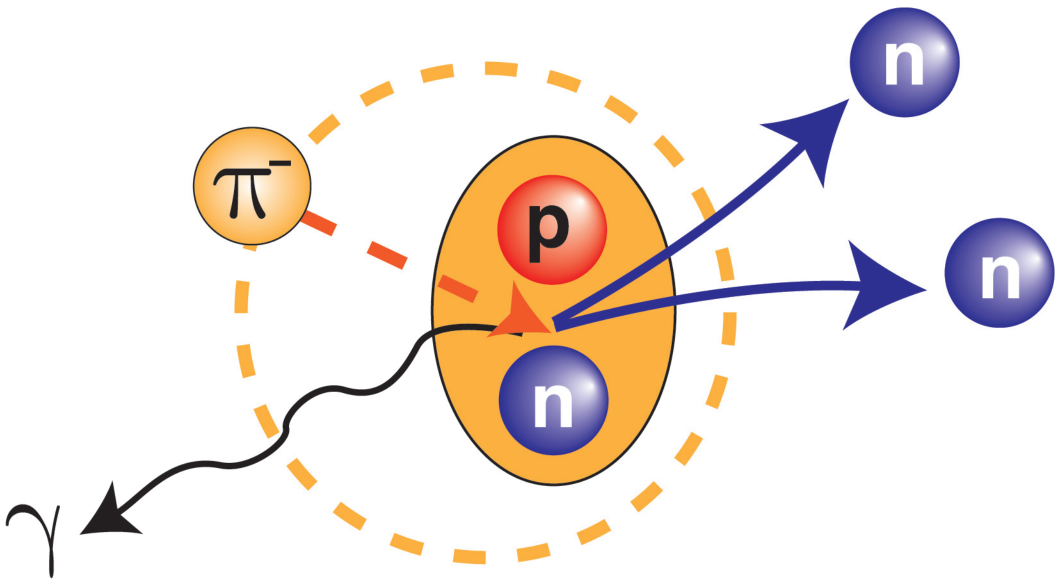

Fig. 1. Schematic picture of radiative pion capture by deuterium.

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